Project SESAMISEED

Experiments to Demonstrate the Practical Uses of Artificial Plasma Clouds in the Lower Ionosphere
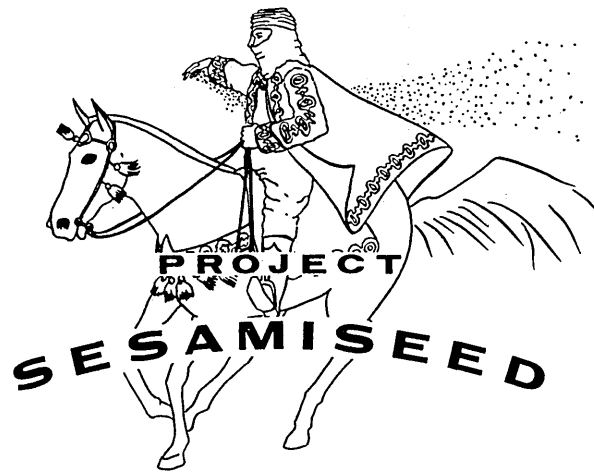
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PROJECT

SESAMISEED

CONTENTS

ABSTRACT

Cesium plasma clouds have been emplaced in the 90 to 103-km altitude region of the ionosphere by rockets and by a 7-in. gun. These clouds have been studied by coherent-pulse-doppler, high-frequency radar for three purposes: (a) to investigate neutral gas and magnetohydrodynamic motions in the clouds, (b) to investigate the role of such motions in forming the plasma clouds into persistent, artificial, sporadic-E patches, and (c) to investigate the potential of such clouds for illuminating the near-over-the-horizon region and detecting small targets in that region.

Parts (a) and (b) of this study are continuing efforts in basic ionospheric research which will be reported elsewhere. This report concerns the third stated purpose, which may be of importance for over-the-horizon surveillance radar.

Evidence has been acquired which demonstrates that the objective of achieving over-the-horizon illumination by this means is possible. Earth backscatter echoes have been found to display an adequately narrow spectral dispersion to permit velocity-discrimination of moving targets. Examples are given of earth backscatter and probable over-the-horizon aircraft echoes from cesium plasma clouds.

PROBLEM STATUS

This is an interim report on one phase of a continuing problem. Work is proceeding on this and several allied subjects.

AUTHORIZATION

PROJECT SESAMISEED
EXPERIMENTS TO DEMONSTRATE THE PRACTICAL USES
OF ARTIFICIAL PLASMA CLOUDS IN THE LOWER IONOSPHERE

INTRODUCTION

Project SESAMISEED is a joint effort supported by the Naval Research Laboratory, the Naval Electronic Systems Command, and the Army Ballistic Research Laboratory, which is intended to explore the lower regions of the ionosphere by means of alkali plasma cloud releases and high-frequency (hf) doppler radar. The acronym SESAMISEED derives from the descriptive title Sporadic E Stimulation by Artificial Metallic Ion SEEDing.

It has been suspected for several years that the formation of sporadic-E (E_s) patches can be stimulated by a sudden injection of energetic charged particles into the E layer under appropriate conditions. Auroral E_s is nearly always associated with solar particle bursts, for example. The notion that E_s patches could be created artificially was suggested by evidence gathered with hf radar that burning rocket motors passing through the lower ionosphere often were followed by persistent, relatively stationary scatterers of some few minutes duration (1). Project SESAMISEED was launched with the purpose of using alkali-seeded plasma clouds emplaced in the E layer to test the feasibility of stimulating the formation of E_s patches which could be used by hf radar to achieve illumination of the near-over-the-horizon region, 200 to 500 mi distant from the radar site.

Two methods have been used for emplacement of the alkali plasma clouds. A 7-in. extended barrel gun, developed by the U.S. Army Ballistic Research Laboratory, has been used to launch 2-kg payloads from the NASA Wallops Island facility into the 90- to 103-km altitude region. Approximately twelve successful launches of this type have been conducted since April 1968, and one of these events is discussed below in detail. The second method of emplacement makes use of a two-stage Nike-Cajun rocket vehicle, which is capable of carrying an 18-kg payload to altitudes above 100 km. To date, two successful rocket launches have been conducted, and both have resulted in bursts at an altitude of 101 km.

All payloads have consisted of a mixture of 34% cesium nitrate, 21% powdered aluminum, 19% cyclonite (RDX), and 26% trinitrotoluene (TNT). This mixture is identical to one which has been used in several post-Firefly programs, and it produces an explosive energy of about 5×10^{13} ergs/kg. Assuming the validity of Brode's (2) model of blast waves in air as interpreted by Groves (3), and that approximately 10^{-4} of the mixture is thermally ionized in the blast phase (4), then the gun-launched vehicles emplace a cloud of 3×10^{21} electrons in a volume of about 5×10^6 m^3 at an altitude of 93 km and in a volume of about 10^7 m^3 at an altitude of 100 km. The rocket-launched vehicles emplace a cloud of nine times this electron population in nine times the volume. Thus, initial electron densities of 3×10^8 to 6×10^8 electrons/cm^3 may be expected.

The blast-wave phase of plasma cloud expansion continues for 5 to 10 sec, depending on altitude and explosive energy, after which the cloud is in pressure equilibrium with its surroundings. Its diffusion and other subsequent evolution depend on neutral-fluid motions in the atmosphere, which are quite strong and highly turbulent in the 90- to 110-km altitude region, and upon magnetohydrodynamic motions due to interactions

involving (a) the ambient electrostatic and magnetostatic fields, (b) fields created by diffusive charge separation, and (c) charge density variations in the plasma cloud. A more thorough description of the initial conditions for these motions, that is, of the blast-wave expansion phase, has been reported elsewhere by Davis and Moore (5). Detailed treatment of the magnetohydrodynamic aspects of the subsequent motion is beyond the scope of this report and is the object of current theoretical and experimental effort at NRL in other phases of Project SESAMISEED.

Observation of the plasma clouds with hf radar from NRL's Chesapeake Beach facility has been used for measurements. High-resolution doppler analysis, achieved with NRL's 60-dB dynamic range radar signal processor, has permitted measurements to be made of turbulence in the plasma clouds and of the spectrally distinctive signatures which probably represent plasma density waves in the clouds. Growth rates, lifetimes, and apparent sizes of these plasma instabilities have been measured and will be reported elsewhere. The evolution of artificial E_s patches from these plasma instabilities, in the cases in which such growth occurred, has also been observed with hf radar, and earth backscatter echoes from these E_s patches have been recorded. It is the growth and behavior of these artificial E_s patches which is the object of this report. It has been found that under some circumstances, clouds of tens-of-minutes duration can be created at altitudes above 100 km. On two occasions, these long-duration clouds have been seen to develop into E_s patches, as evidenced by the acquisition of earth-backscatter echoes which were reflected from the cloud to the earth and back to the radar site by the same path.

On one of these occasions, an NRL aircraft was flown in the near-over-the-horizon region, about 250 naut mi from the radar. Although this position was found later not to have been optimum for illumination via the artificial E_s patch, a likely aircraft echo was detected for a few minutes. In addition, on this same occasion, a larger and longer duration probable aircraft echo was acquired. This second target could not be identified and must be regarded as a likely anonymous aircraft, perhaps from the Naval Air Station, Norfolk, which happened to pass beneath the cesium cloud shortly after its deployment. Analysis of the earth backscatter and probable aircraft data appear in the next section of this report.

DATA AND ANALYSIS

Gun-Launched 2-kg Cesium Cloud of Feb. 14, 1969

During the dawn period of Feb. 14, 1969, a 2-kg package of the cesium high-explosive mixture was burst at an altitude of about 93 km over Wallops Island, Virginia. The burst occurred approximately 15 minutes after sunrise at the burst height. The lower ionosphere was illuminated by 15.6-MHz radiation at a 2.3-Mw peak power from the NRL hf Advanced Research Radar, located at a slant range of about 100 naut mi from the cloud.

The cloud echo data were analyzed using two techniques. The first technique utilizes NRL's 60-dB-dynamic-range doppler analysis processor to give a range-gated display of radar data in a doppler shift vs time format. Figure 1 is an example of this display, showing the direct cloud echo for its entire duration. A horizontal bar at 0 Hz on Fig. 1 marks the position of the carrier frequency, with positively doppler shifted signals above and negatively doppler shifted signals below it. The blast wave is indicated by the bright vertical bar at 1125:20 GMT and occupies approximately 6 sec of the time
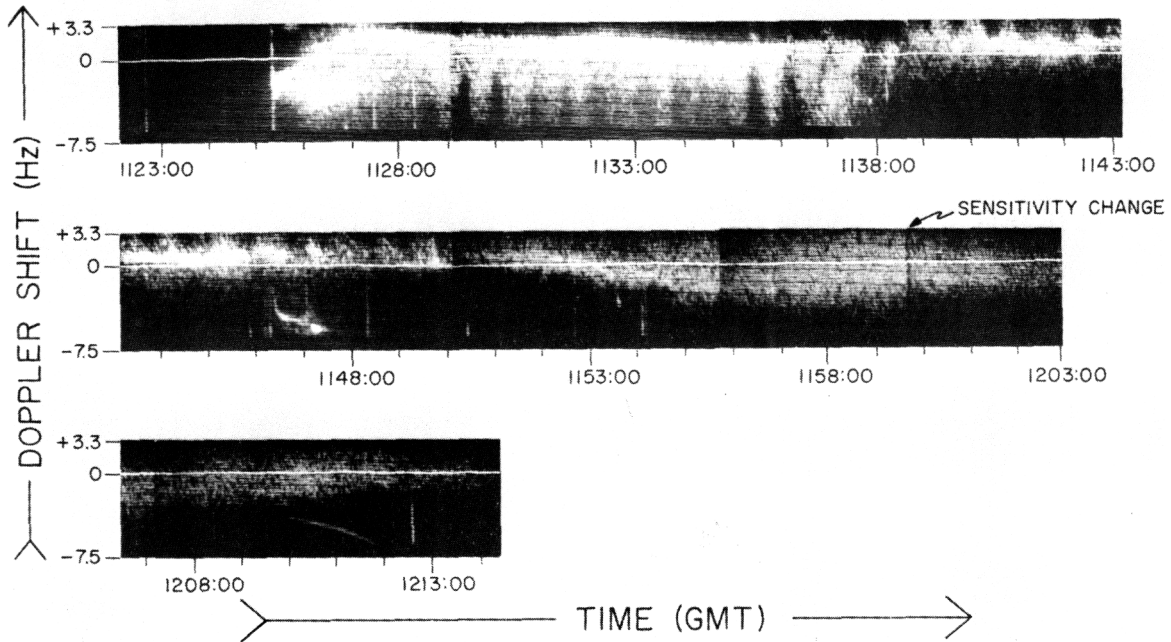
Fig. 1 (U) - Doppler shift vs time for the cesium plasma cloud of Feb. 14, 1969. The data are displayed by utilizing NRL's 60-dB dynamic range doppler analysis processor.

base. The subsequent behavior of the signature is dominated by strikingly periodic modulations in spectral bandwidth with a period of about 50 sec. There occur abrupt disappearances of the signal at 1138:00, and again at 1150:00, with a distinct change in character of the signal after the latter time. The signal then becomes diffuse and gradually fades until, at about 1214:00, it is rapidly dropping into the noise. The irregular negative-doppler trace between 1146 and 1148 is probably a meteor echo. The short curved trace between 1210 and 1212 is a line-of-sight aircraft which should be regarded as a contaminant.

(U) The 50-sec modulations in spectral bandwidth are a likely manifestation of collective behavior within the plasma cloud. The most promising candidate for explaining these modulations is a dissipative plasma instability, probably dependent for its existence on a fortuitous geometrical configuration that exists between (a) the electron density gradient in the cloud, (b) an electrostatic field resulting from either charge separation in the cloud or in the ambient, and (c) the geomagnetic field. Of concern for this treatment is the wide spectral distribution of the direct plasma cloud echo, which occupies as much as 10 Hz at times and seldom becomes narrower than 3 Hz.

(U) Figure 2 is an example of the second form of data analysis, which illustrates more graphically the spectral distribution of energy from the cloud echo. This type of display, which permits a third dimension (in this case spectral amplitude) to be displayed, was acquired by employing a fast fourier transform for handling the data on a CDC 3800 computer located at NRL. In addition to the diffuse character of the signature, and the modulations in spectral bandwidth between 1124 and 1147, there occur short-duration spectrally narrow signals frequently during the cloud's lifetime. Examples are the large,
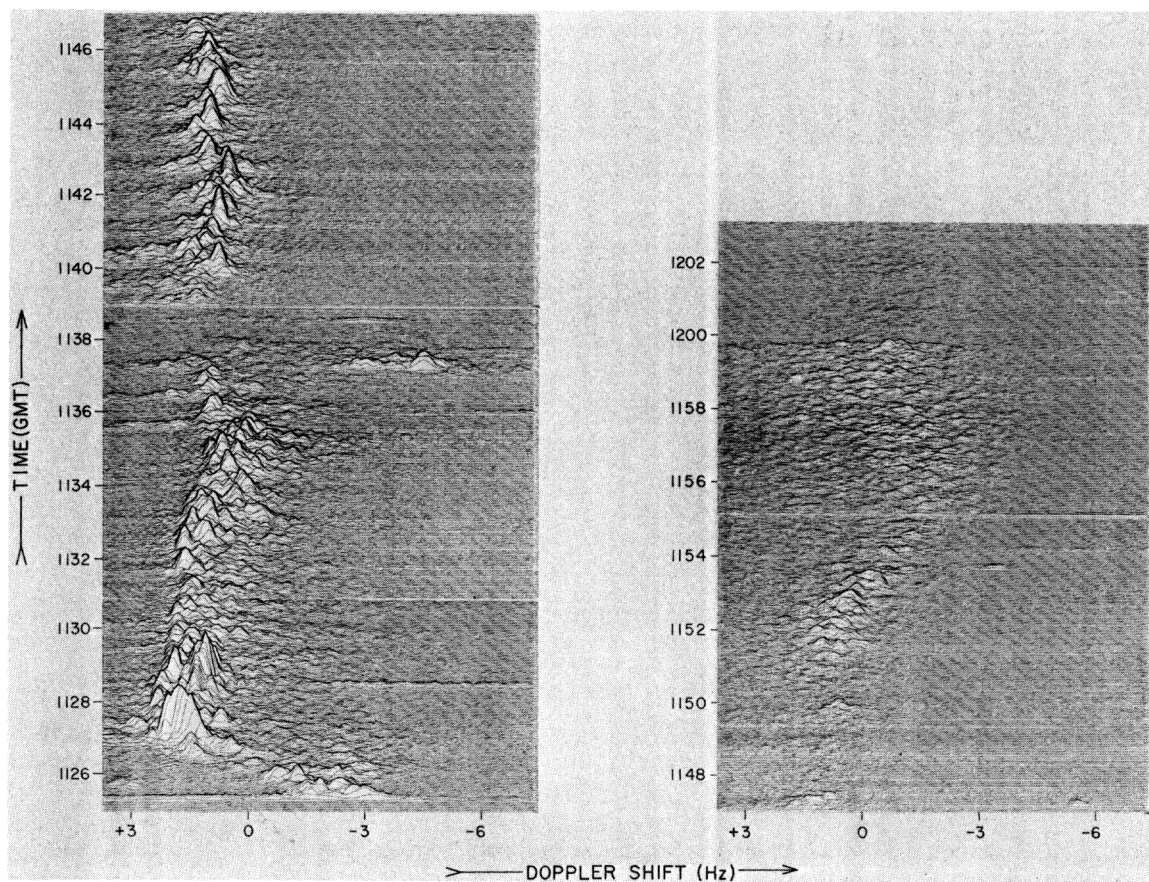
Fig. 2 (U) - Computer-generated plot of doppler shift vs time for the same cesium plasma cloud as shown in Fig. 1. In this method of data analysis the spectral distribution of energy is also presented.

narrow, ridge-like trace at about 1127, and several sharp peaks between 1140 and 1146. Features of this type are common in cesium plasma clouds at E-layer heights, and present information suggests that they arise from plasma instabilities which play a role in the formation of a persisting artificial E_s patch from an alkali plasma cloud. The display in Fig. 2 is presented here as a basis upon which the earth backscatter spectrum may be contrasted, and it should be noted that low-level spectral components fill half of the available 11.25-Hz doppler spectrum. The integration time used for the fast fourier transform was 2 sec, and so a spectral resolution of about 0.5 Hz is contained in Fig. 2.

(U) Figure 3 is a plot of apparent radar cross section vs time for the direct cloud echo. A sudden increase in cross section from about $5 \times 10^3 m^2$ (the effective noise level) to about 10^7 m^2 occurs at the time of burst, and this increase is followed by a gradually changing apparent target cross section which varies between 10^6 and 10^7 m^2, with occasional descents in size to 10^4 m^2. Between 1136 and 1150 GMT obvious cyclic changes with a 50-sec period occur in the radar cross section. These variations are in phase with the doppler spectrum modulation, that is, their peaks correspond to peaks in the
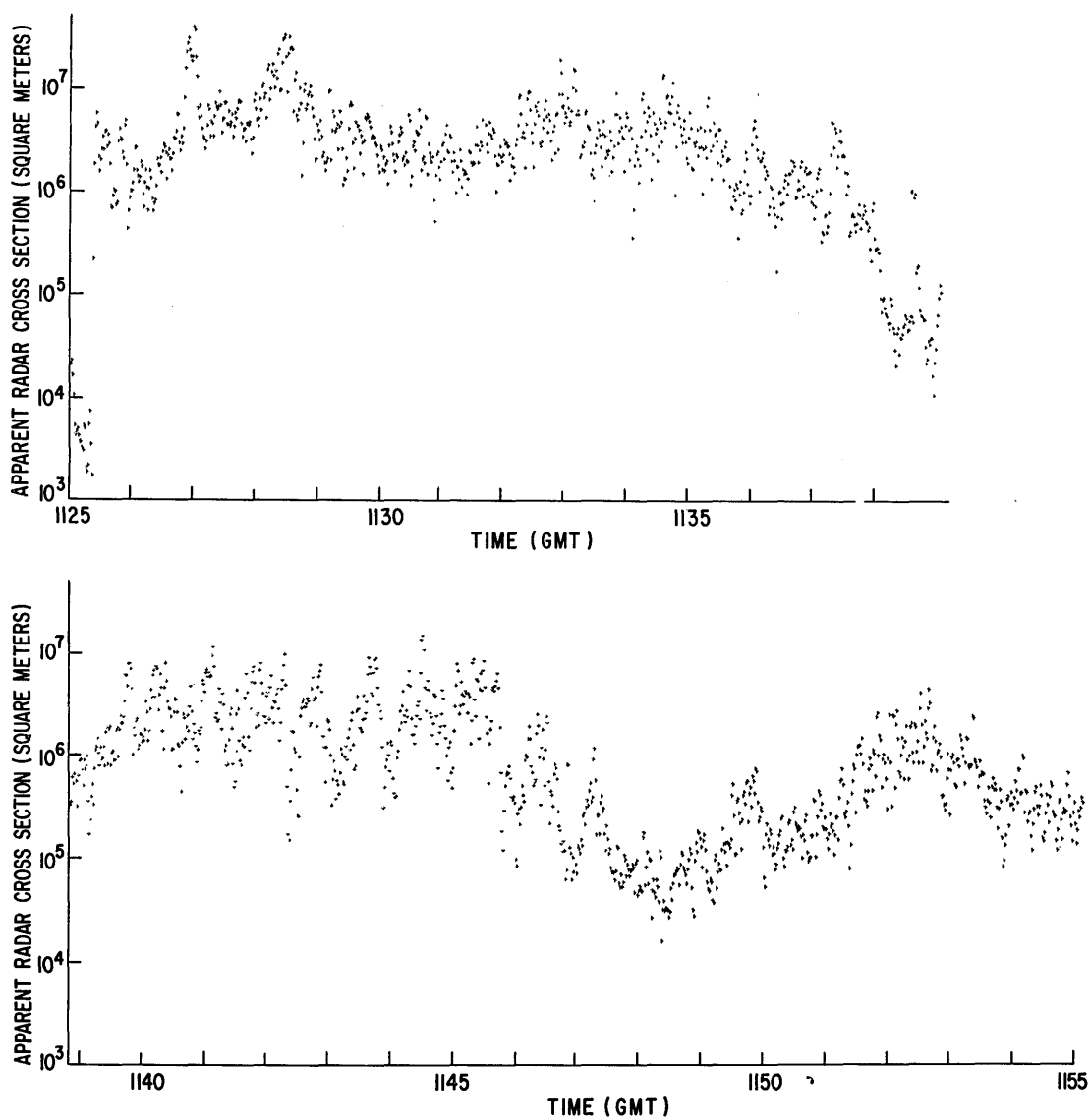
Fig. 3 (U) - Plot of apparent radar cross section vs time
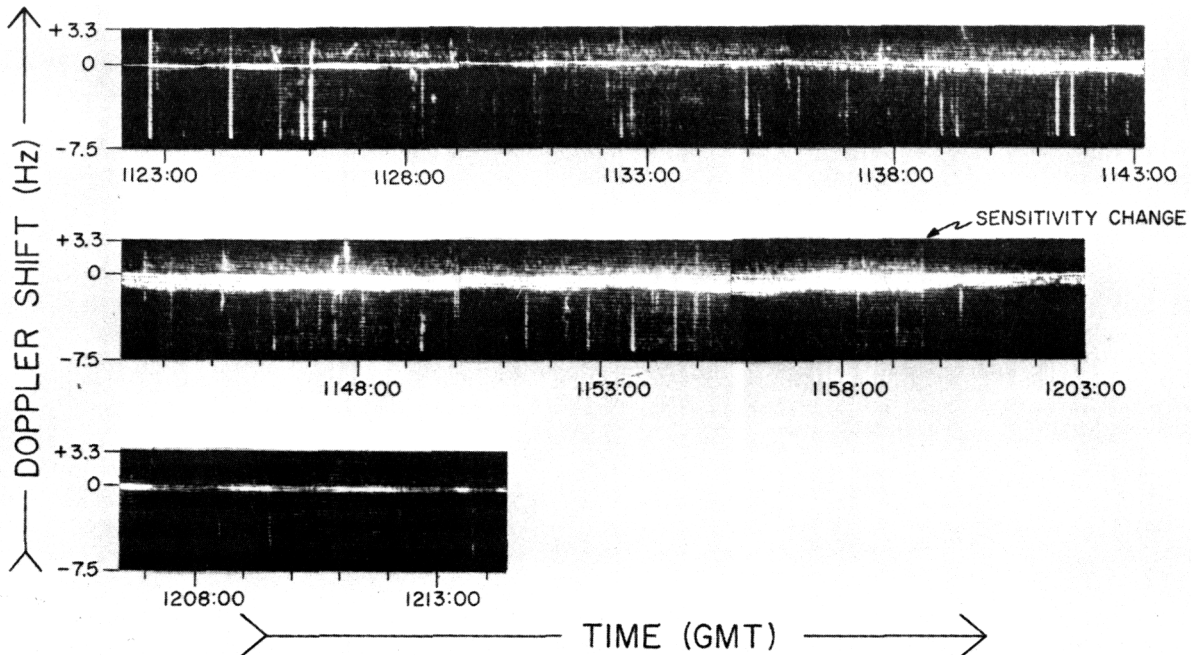for the cesium plasma cloud of Feb. 14, 1969

Fig. 4 (U) - Doppler shift vs time for an earth backscatter echo on
Feb. 14, 1969. The echo occurred over the path from transmitter
to cloud to earth and then back again to the cloud and the receiver.

spectral bandwidth. For the purposes of this report, the only matter of interest is the
10- to 20-dB modulation depth of the radar cross-section fluctuations for the direct cloud
echo.

(U) Figure 4 is a display of an echo obtained over twice the range to the plasma cloud
and represents an earth backscatter echo which occurred over the path of transmitter-
cloud-earth-cloud-receiver. There is a small, narrow-spectrum, spurious signal at 0 Hz
throughout the display, which can be ignored. The earth backscatter echo begins to rise at
about 1130:00, although it cannot be distinguished from the spurious signal until about
1138:00. It gradually rises and broadens slightly in spectral bandwidth until about 1159:00.
Notice that, in contrast to the direct cloud echo, there is no apparent modulation in its
spectrum and no signal dropouts. The spectrum is never more than about 2 Hz wide, and
there are no low-level diffuse components. After the sensitivity change at 1159:40, the
backscatter echo declines in strength and is essentially absent after 1206:40 (it probably
disappeared during the radar down-time between 1203:12 and 1206:36).

(U) Figure 5 is a computer-generated version of the earth backscatter echo signature
which illustrates its relatively discrete spectrum in comparison with Fig. 2.

(U) Figure 6 is a plot of apparent radar cross section vs time for the earth back-
scatter echo, beginning at about 1131 near the noise level $(5 \times 10^3 \, \text{m}^2)$. A note of explanation
is appropriate here. It is assumed for the purposes of these calculations that the plasma
cloud is a perfect planar reflector which specularly reflects all electromagnetic energy
incident upon it. This assumption is consistent with the belief that the plasma cloud spreads
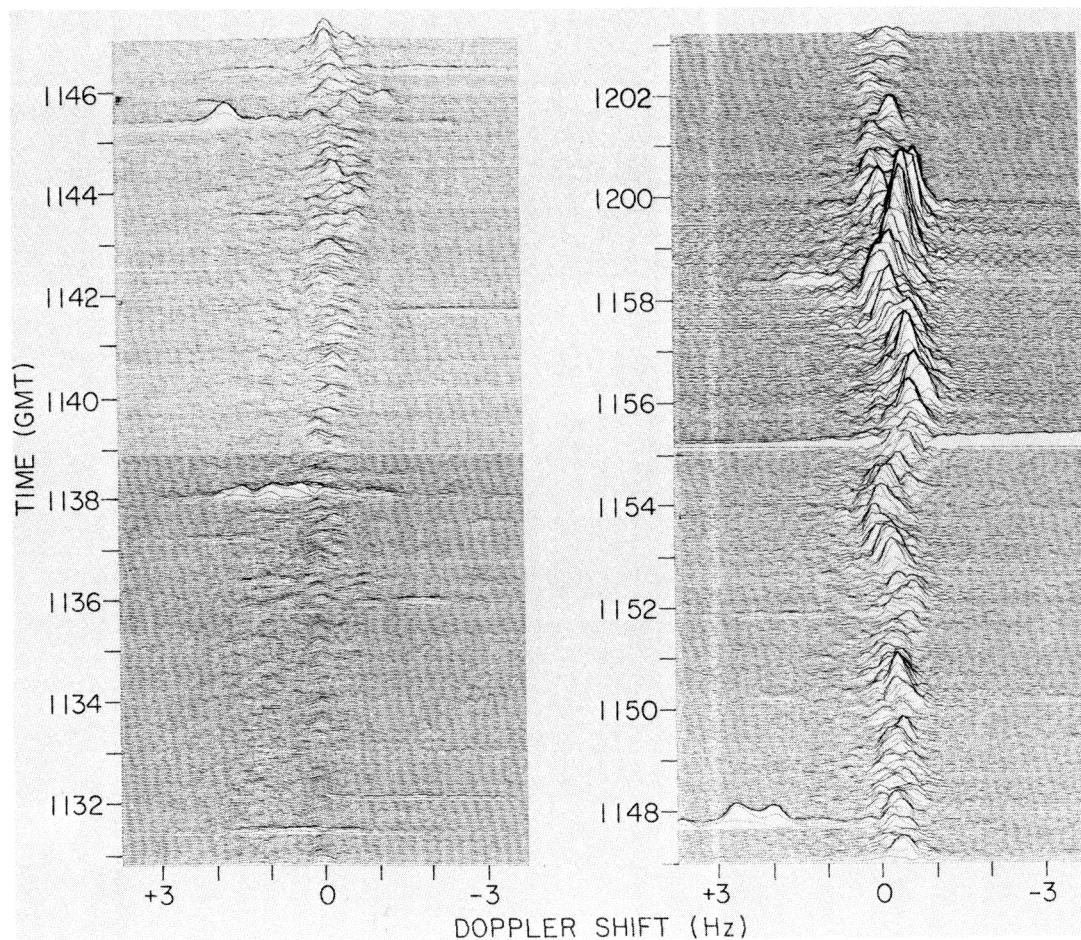
Fig. 5 (U) - Computer-generated plot of doppler shift vs time for the same earth backscatter echo as shown in Fig. 4. The short-duration, wide-spectrum bumps are occasional meteor echoes and not part of the earth backscatter.
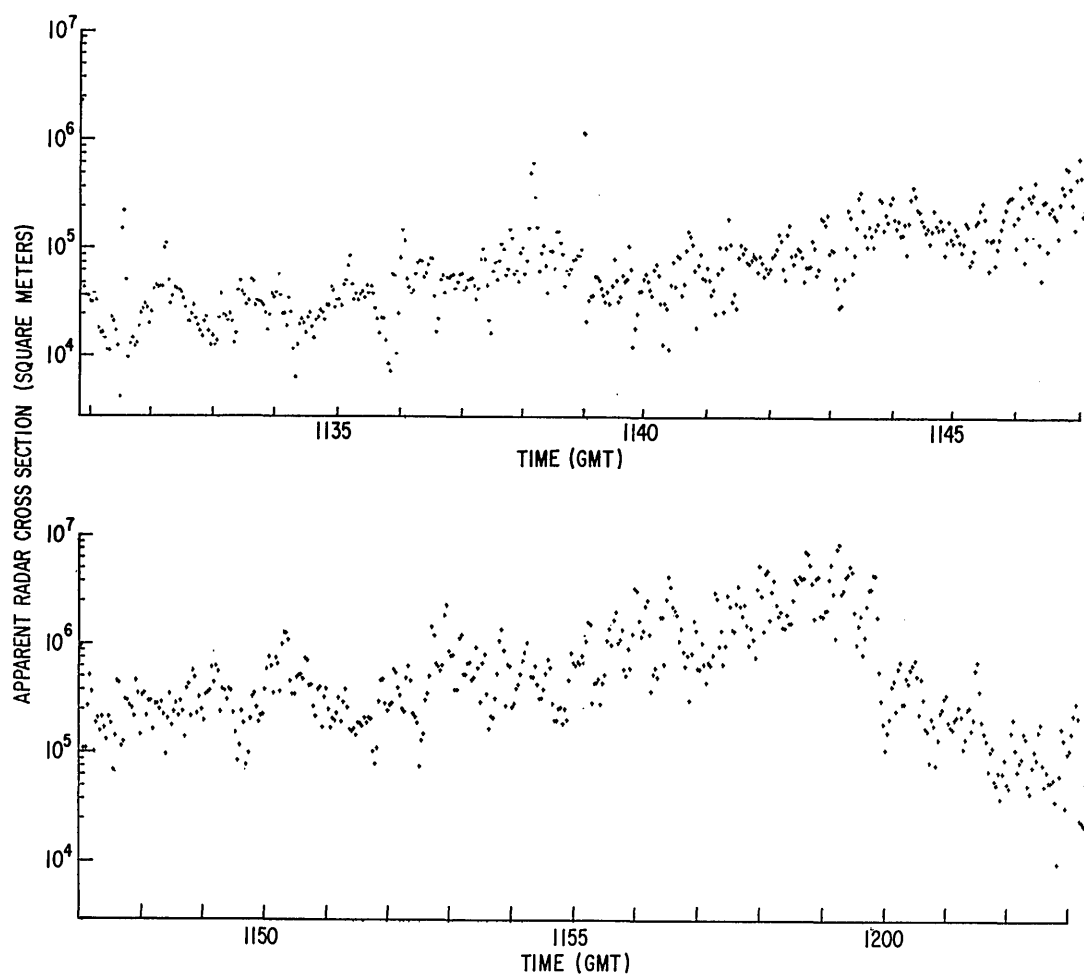
Fig. 6 (U) – Plot of apparent radar cross section vs time for the
earth backscatter echo shown in Figs. 4 and 5

horizontally into a dense E_s-like patch, but is not based on actual knowledge of its shape. The apparent radar cross section of this signal grows gradually, with modulations in amplitude of about 10 dB, to a maximum size of nearly $10^7 m^2$ at 1159. The sudden drop in size at 1159:40 is an artifact which resulted from a change in receiver gain. With the exception of the last 5-min period shown in Fig. 6, the earth echo fluctuates between 10^5 and $10^6 m^2$, and these values are not inconsistent with the measured cloud cross section of about $10^7 m^2$ and an assumed earth scattering loss of about 15 dB. This agreement is valid only if the cloud is an isotropic scatterer, of course. If the cloud is directive, as would be the case of a pancake-like patch of high electron density, then its forward-scattering cross section would be much larger than its backscattering cross section. The final peak in the earth backscatter radar cross section of Fig. 6 is about $10^7 m^2$. If the 15-dB assumed ground reflection loss is retained, than a forward-scattering cross section of between 10^8 and $10^9 m^2$ must be ascribed to the plasma cloud at that time, when its backscattering cross section is about $10^6 m^2$. Hence, the profile of electron density which bounds the effective area for forward scattering (about half the electron density which is necessary for backscattering) must be more than a hundred times larger in cross-sectional area than the profile effective for backscattering.

Rocket-Launched 18-kg Cesium
   Cloud of Aug. 28, 1969

       Figure 7 illustrates both the direct plasma cloud echo and a sample of data range-gated at 250 naut mi (1803 to 1817 GMT) and 170 naut mi (1817 to 1831 GMT) from the cesium released at an altitude of 101 km on Aug. 28, 1969. Radar parameters were similar to those in the Feb. 14 release. The direct cloud echo (Fig. 7(a)) is characterized by a rather diffuse spectrum, which displays some evidence of cyclic variations in the spectral dispersion and in the position of the spectral minimum with a 7-min period. There also appear indications of discrete target echoes between 1820 and 1825. These echo traces were identified as spillover from targets at nearby ranges, resulting from the circumstance that the transmitted pulse has a cosine-squared character, with leading and trailing edges which extend beyond one range-bin width. The upper trace was identified as a line-of-sight target at closer than 120 naut mi, and the lower trace was identified as a probable over-the-horizon aircraft at an actual range of 170 naut mi. The lower display (Fig. 7(b)) shows the latter target, at its true range position, between 1817 and 1828 GMT. This anonymous target is presented as evidence that an alkali plasma cloud can be used to illuminate the near-over-the-horizon region and permit observations of aircraft targets for periods of several minutes. Several other features of Fig. 7 are of interest. It should be noted that a replica of the early direct cloud echo appears from 1805 to 1811 on the lower display. This trace represents a possible earth backscatter echo from the plasma cloud, or it may be a manifestation of the adjacent-range spillover described above. (In Fig. 9 below an example will be given of a definite computer-analyzed earth backscatter echo, at even greater range, which was acquired from the plasma cloud at a later stage of its evolution.) There also appears a diffuse echo at near-zero doppler shift between 1817 and 1830. This trace is due to adjacent-range spillover of this later earth backscatter echo. The faint trace between 1809 and 1812 is believed to be an echo from NRL's aircraft, which was stationed 250 naut mi from the radar site, at a position about twice the expected range to the cloud. This position, as it developed, was not well illuminated by the cloud, and this small trace was detected only briefly.

       Figure 8 is a doppler-shift-vs-range display showing the large aircraft target at 170 naut mi, the plasma cloud direct echo at 120 naut mi, and normal ionospheric earth backscatter at 600 to 900 naut mi. The aircraft echo is spectrally discrete and
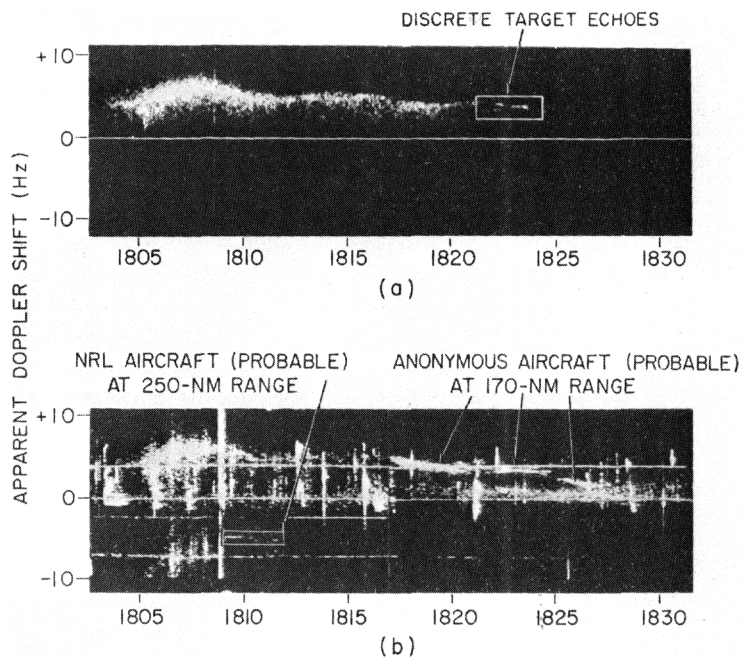
Fig. 7 - Apparent doppler shift vs time for (a) cesium plasma cloud of Aug. 28, 1969, at a range of 120 naut mi and (b) range-gated target echoes at 170 and 250 naut mi
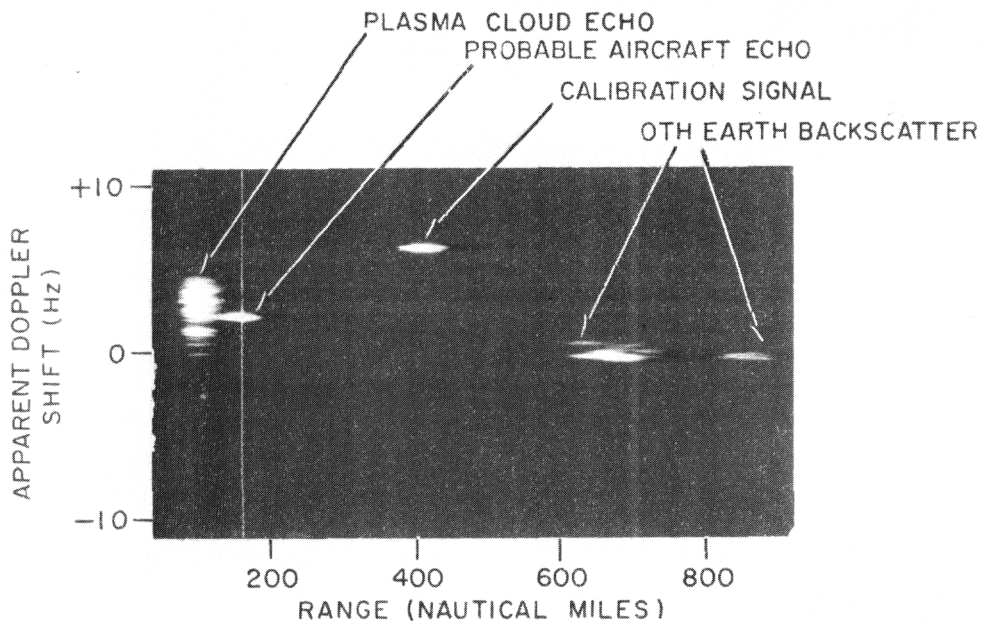

Fig. 8 - Apparent doppler shift vs range for echoes received from the cesium plasma cloud and for normal ionospheric earth backscatter, Aug. 28, 1969

range discrete and appears at a time which coincides with the expected period of maximum earth illumination by the cloud. The possibility that it could be from a line-of-sight aircraft at a 30,000 to 40,000-ft altitude cannot be completely discounted, although line-of-sight targets at that range are very infrequent in the Virginia Capes region, and no other targets were seen beyond the usual 100-naut-mi line-of-sight range limit during the entire operation. That the large aircraft echo in Figs. 7 and 8 does indeed arise from a true over-the-horizon target, however, is strongly indicated by the fact that it displays a regular fading pattern with a period of 3-1/3 to 4 min. This behavior is normal for plane-polarized radiation in a magnetoionic medium, and in this case the rotation of the plane of polarization which gives rise to the fading can be attributed to its passage through a portion of the plasma cloud.

Figure 9 is a computer-analyzed version of the earth backscatter echo which appeared at a 300-naut-mi range due to illumination by the cesium cloud. That this signature is not perfectly specular, but instead displays a two-component, and sometimes a three-component, spectrum with a 4-Hz total spectral dispersion, is evidence that this plasma cloud did not form itself into a single E_s-like reflecting layer as did the earlier example. Instead, this cloud probably developed into several smaller patches, each of which moved at a different speed, and hence imposed a slightly different doppler shift on its earth backscatter echo. The multiple character of the scattering is also manifested on the probable aircraft echo, particularly in the 1817 to 1821 GMT period in Fig. 7. Presumably this target was illuminated by a combination of paths which used the several scattering blobs for reflection, and as a result is more diffuse than a usual hard-target echo.

Figure 10 is a plot of apparent radar cross section vs time for the earth echo. It rises abruptly to a peak value of about $3 \times 10^6 m^2$, and gradually declines to the effective noise level of about $3 \times 10^4 m^2$ in about 4 min time. The maximum size of $3 \times 10^6 m^2$ is consistent with the cloud size of about $10^8 m^2$, allowing an earth scattering loss of about 15 dB.

CONCLUSIONS AND RECOMMENDATIONS

It has been shown that earth backscatter echoes may be obtained, under appropriate conditions, from artificially emplaced alkali plasma clouds in the lower ionosphere. Of particular importance is the circumstance that these backscatter echoes are narrow in spectral dispersion by comparison to the normally diffuse direct cloud echoes, indicating that cloud motion is principally horizontal. This feature permits targets in the near-over-the-horizon region to be illuminated monochromatically in a coherent-pulse-doppler sense, and hence target discrimination on the basis of velocity is possible.

It has been demonstrated with reasonable veracity that over-the-horizon aircraft targets may be detected for periods of several minutes by these means.

Several matters, which remain to be explored, are:

1. Operations to date have been confined to altitudes of 103 km and below. The 7-in. gun system is limited to 100 km for reliable operation, and cannot be used to probe the 103- to 120-km altitude region, in which conditions for creation of a long-persistence cloud are most favorable. An extended series of rocket-launched vehicles should be conducted to investigate this higher altitude region.
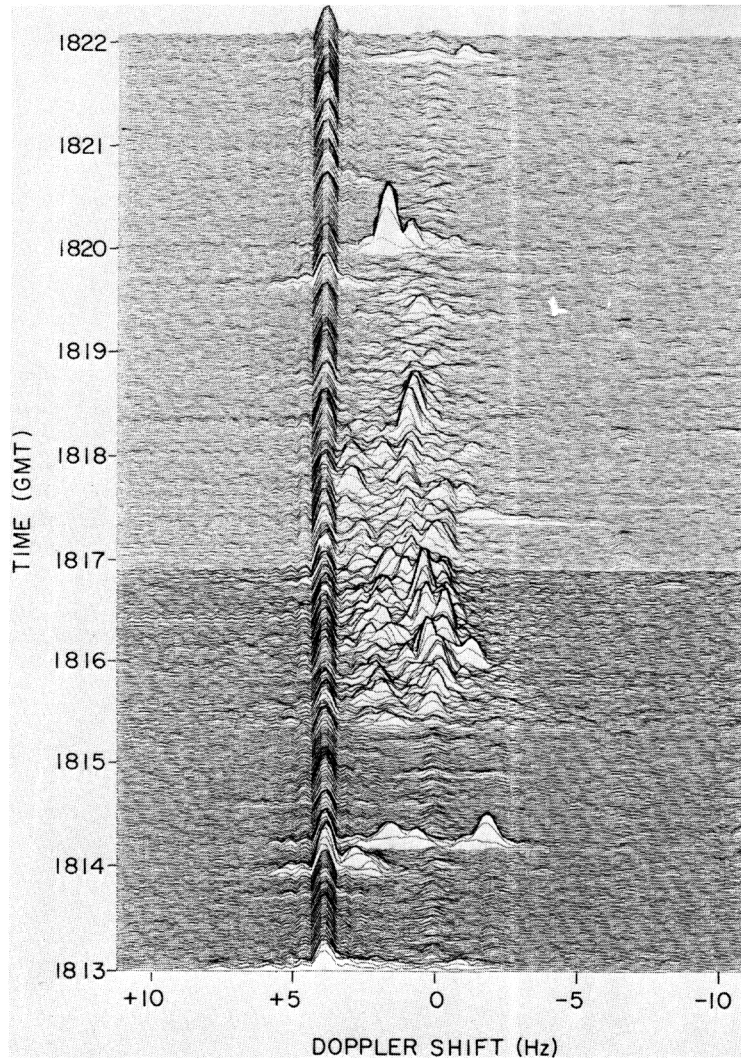
Fig. 9 (U) - Computer-analyzed plot of doppler shift
vs time for the earth backscatter echo associated
with the Aug. 28, 1969, cesium plasma cloud launch

     2. The effect of payload size should be studied, especially in view of the fact that
the larger, more persistent earth backscatter echo was obtained with a 2-kg package.
Thus several sizes of payload should be tested to determine an optimum configuration.

     3. The importance of solar illumination should be investigated. The most spectacular
results to date have been obtained during the dawn period when solar illumination is in-
creasing in a largely depleted E region. Midday and midnight periods also should be studied.

     4. The correlation of successful plasma cloud creation with the presence and altitude
of natural E_s, and with winds in the lower ionosphere, should be investigated to determine
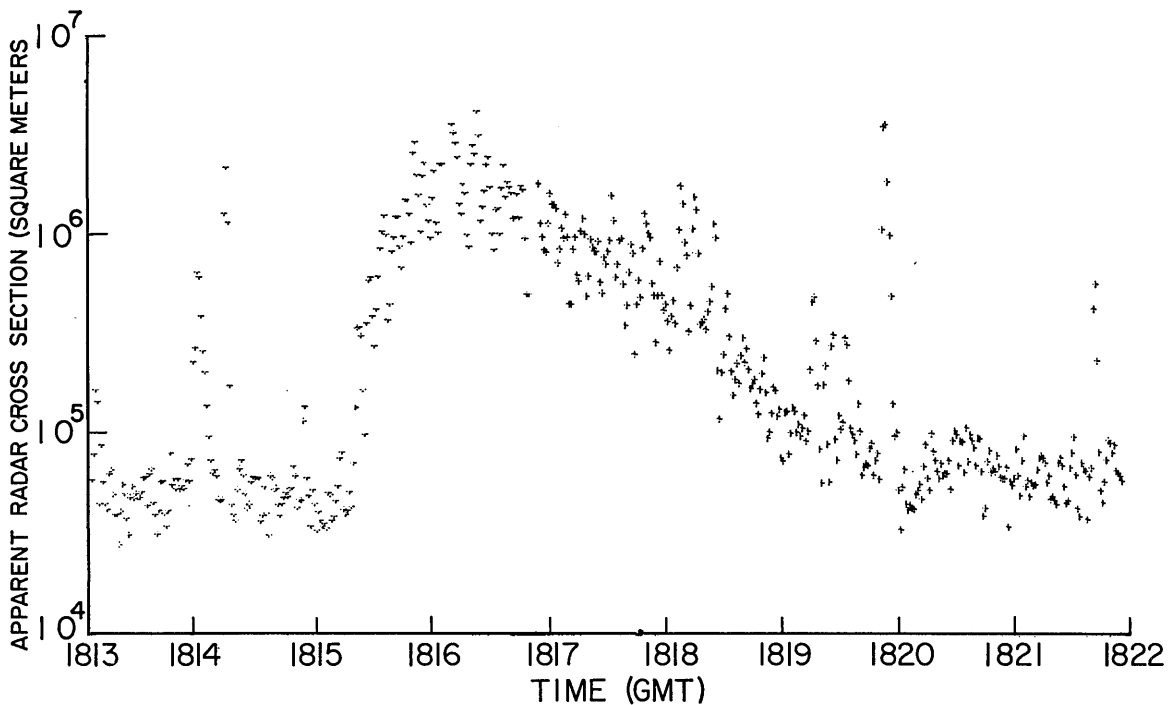the conditions most favorable for creation of a persistent cloud.

Fig. 10 (U) - Apparent radar cross section vs time for the earth backscatter echo of Aug. 28, 1969. The effective receiver noise level is about $3 \times 10^4 \text{m}^2$.

5. Investigations should be undertaken with more target aircraft, distributed geographically, and perhaps with slowly moving surface targets, to determine limits on over-the-horizon illumination coverage and velocity discrimination.

(U) These investigations should permit estimates to be made of what cloud persistence times, target detection times, coverage areas, and tracking accuracy in range and velocity can be expected.

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13. ABSTRACT

Cesium plasma clouds have been emplaced in the 90 to 103-km altitude region of the ionosphere by rockets and by a 7-in. gun. These clouds have been studied by coherent-pulse-doppler, high-frequency radar for three purposes: (a) to investigate neutral gas and magnetohydrodynamic motions in the clouds, (b) to investigate the role of such motions in forming the plasma clouds into persistent, artificial, sporadic-E patches, and (c) to investigate the potential of such clouds for illuminating the near-over-the-horizon region and detecting small targets in that region.

Parts (a) and (b) of this study are continuing efforts in basic ionospheric research which will be reported elsewhere. This report concerns the third stated purpose, which may be of importance for over-the-horizon surveillance radar.

Evidence has been acquired which demonstrates that the objective of achieving over-the-horizon illumination by this means is possible. Earth backscatter echoes have been found to display an adequately narrow spectral dispersion to permit velocity-discrimination of moving targets. Examples are given of earth backscatter and probable over-the-horizon aircraft echoes from cesium plasma clouds.

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Project SESAMISEED Ionosphere Geomagnetism Sporadic E layer Pulse doppler radar Coherent radar Dispenser bombs Alkali metals Cesium Charged particles Plasmas (physics) Plasma density Rocket assisted projectiles Over the horizon detection						

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